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Sneddon

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(54) **THERMAL ENERGY RECOVERY**

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F28D 19/00	(2006.01)
F15B 1/02	(2006.01)
F28D 15/00	(2006.01)
B60T 8/44	(2006.01)

(52) **U.S. Cl.**

CPC ***F15B 1/025*** (2013.01); ***F28D 15/00*** (2013.01); ***F28D 19/00*** (2013.01); *B60T 8/443* (2013.01)

(58) **Field of Classification Search**

CPC F28D 15/00; F28D 19/00; F28D 20/00; F28D 20/0034; F28D 21/00; F28D 2020/006; F28D 2020/0078; F28D 2020/0082; F28D 2020/0095; F28D 2020/0086; F28D 2021/008; B60T 8/443; B60T 1/10; B60W 30/18127; Y02T 10/90; F15B 1/025

USPC 417/243; 418/83, 206.3; 280/212; 180/165; 60/408, 413, 414, 419

See application file for complete search history.

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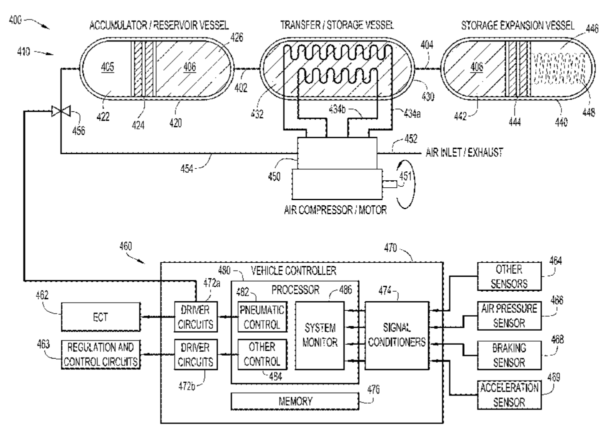
(57) **ABSTRACT**

Towards recovering thermal energy, an accumulator buffers a working fluid over an energy recovery cycle that includes two processes: one in which working fluid is accumulated in the accumulator at increasing pressure and the other that draws working fluid from the accumulator at decreasing pressure. Heat storage fluid is displaced in a storage fluid conduit towards a heat storage region in response to increasing pressure in the accumulator and towards a reservoir region in response to decreasing pressure in the accumulator. One or more heat exchange conduits traverse the storage fluid conduit to come in thermal contact with the heat storage fluid where they transfer heat to the heat storage fluid during the first process of the energy recovery cycle and transfer heat from the heat storage fluid during the other process.

13 Claims, 7 Drawing Sheets



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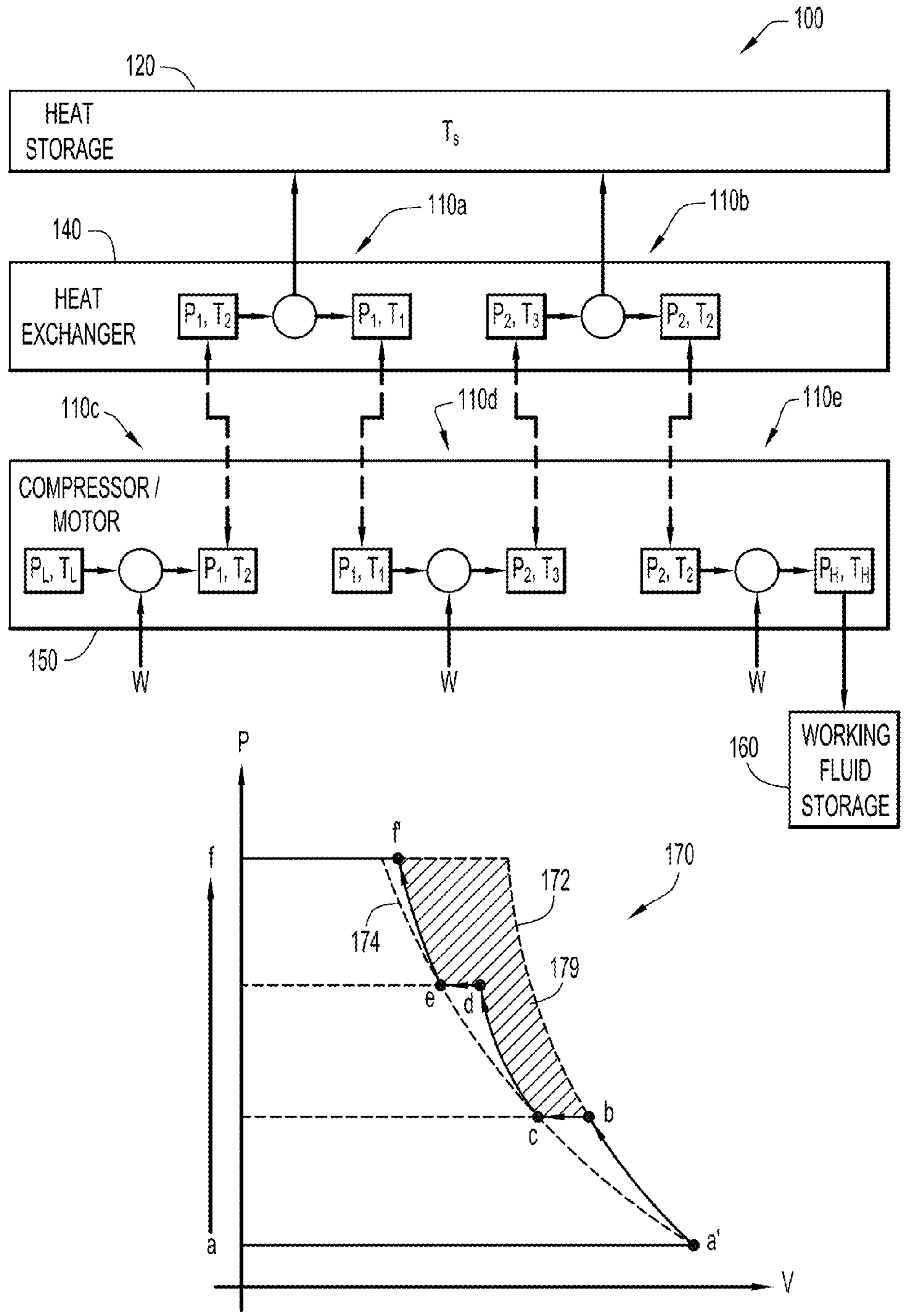

100
120
HEAT
STORAGE
T_s
110a
110b
140
HEAT
EXCHANGER
P_1, T_2
P_1, T_1
P_2, T_3
P_2, T_2
110c
110d
110e
COMPRESSOR /
MOTOR
P_L, T_L
P_1, T_2
P_1, T_1
P_2, T_3
P_2, T_2
P_H, T_H
150
W
W
W
160
WORKING
FLUID
STORAGE
P
f
f'
170
172
174
179
e
d
b
c
a
a'
V

FIG.1A

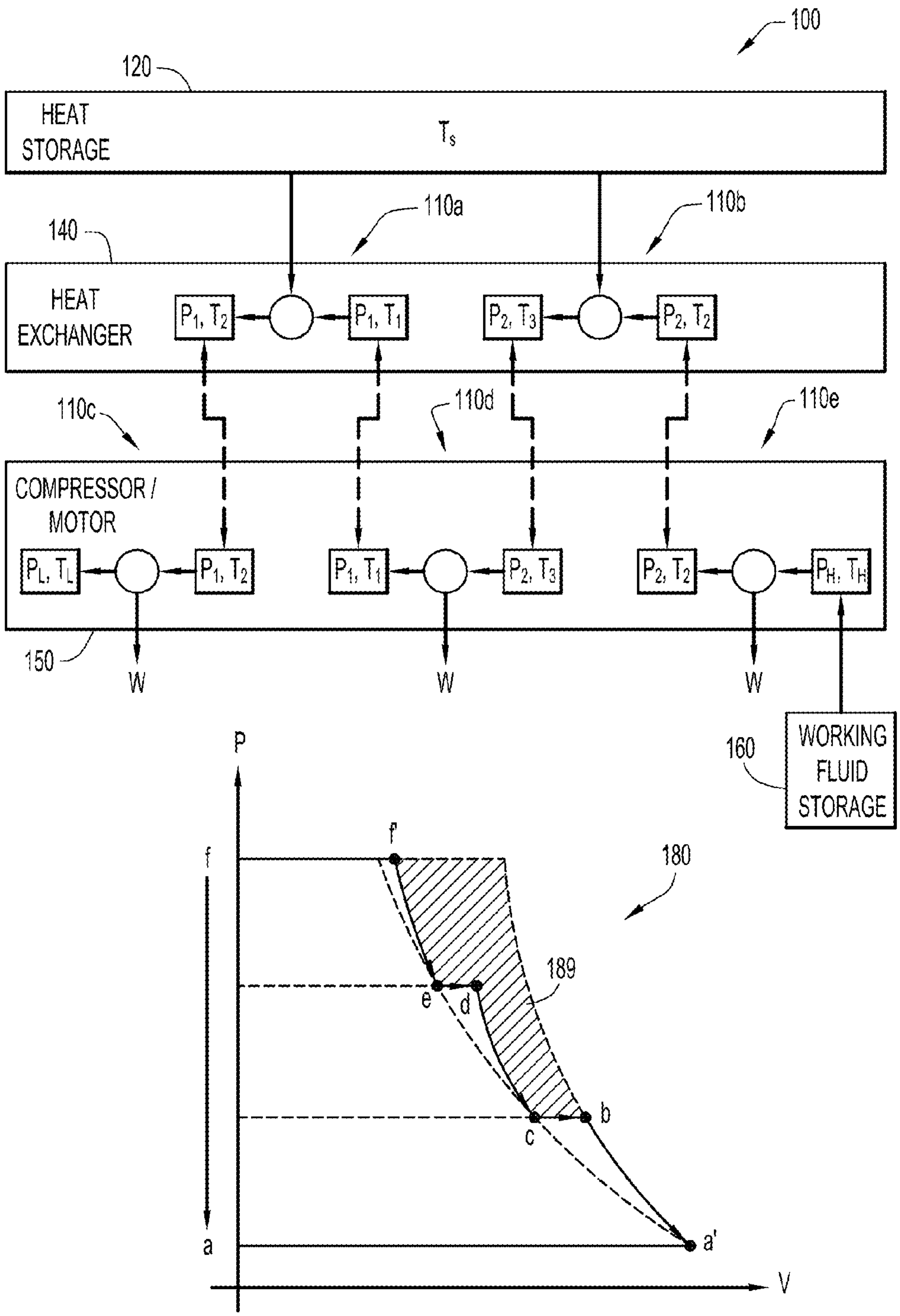

100
120
HEAT STORAGE
T_s
110a
110b
140
HEAT EXCHANGER
P_1, T_2
P_1, T_1
P_2, T_3
P_2, T_2
110c
110d
110e
COMPRESSOR / MOTOR
P_L, T_L
P_1, T_2
P_1, T_1
P_2, T_3
P_2, T_2
P_H, T_H
150
W
W
W
160
WORKING FLUID STORAGE
P
f
f'
180
189
e
d
c
b
a
a'
V

FIG.1B

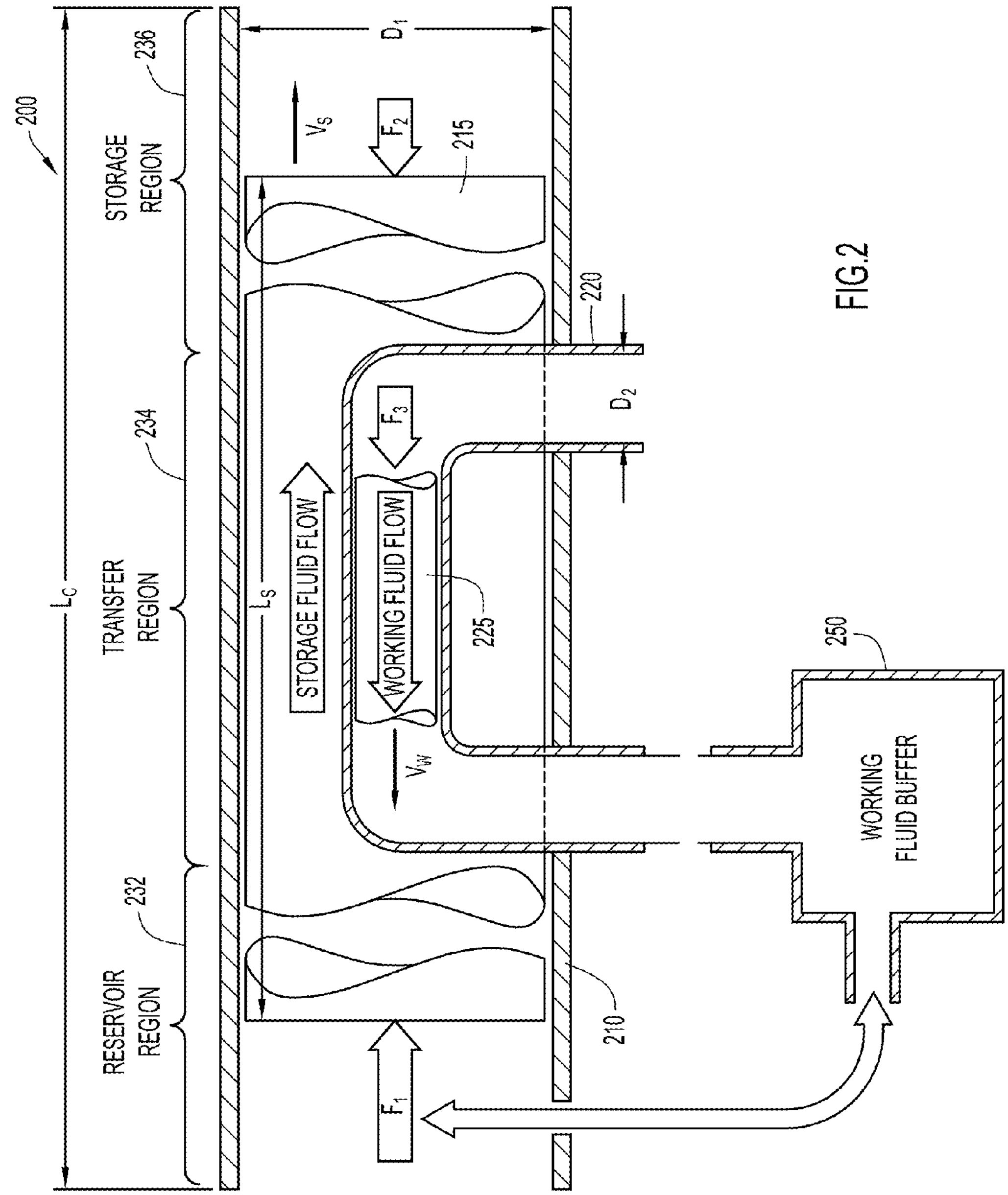

200
236
STORAGE REGION
234
TRANSFER REGION
232
RESERVOIR REGION
L_C
L_S
D_1
V_S
F_2
215
220
D_2
F_3
STORAGE FLUID FLOW
WORKING FLUID FLOW
225
V_W
250
WORKING FLUID BUFFER
210
F_1

FIG.2

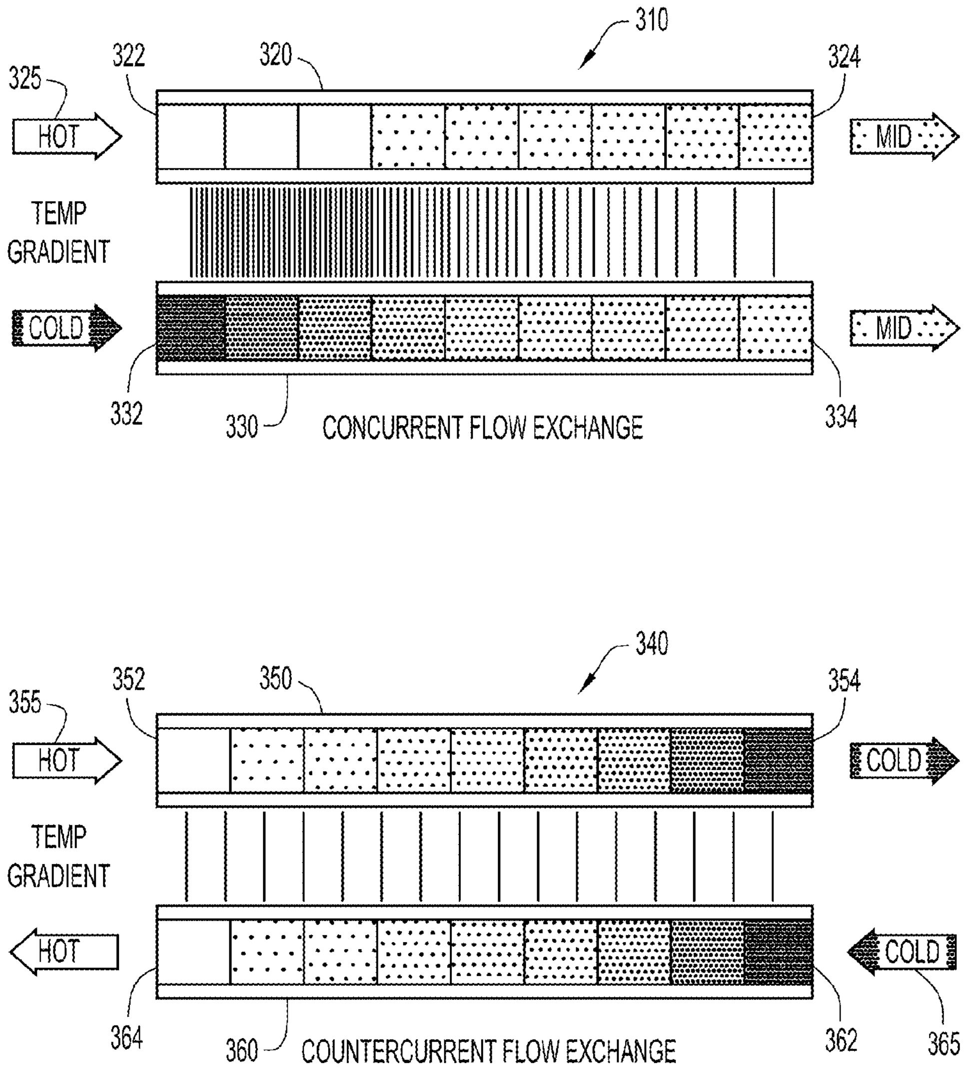

310
322
320
324
325
HOT
MID
TEMP
GRADIENT
COLD
MID
332
330
CONCURRENT FLOW EXCHANGE
334
340
352
350
354
355
HOT
COLD
TEMP
GRADIENT
HOT
COLD
364
360
COUNTERCURRENT FLOW EXCHANGE
362
365

FIG.3

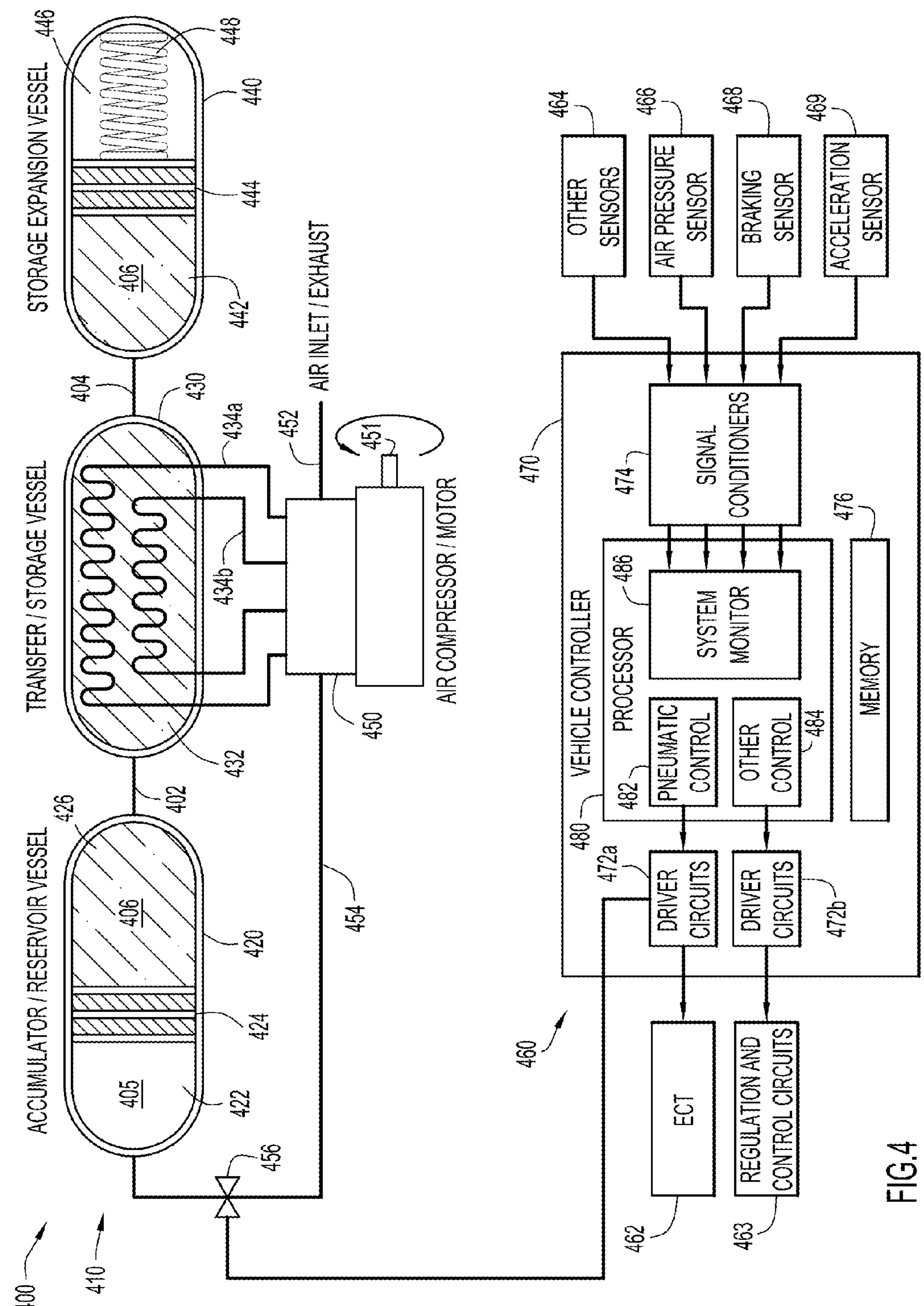
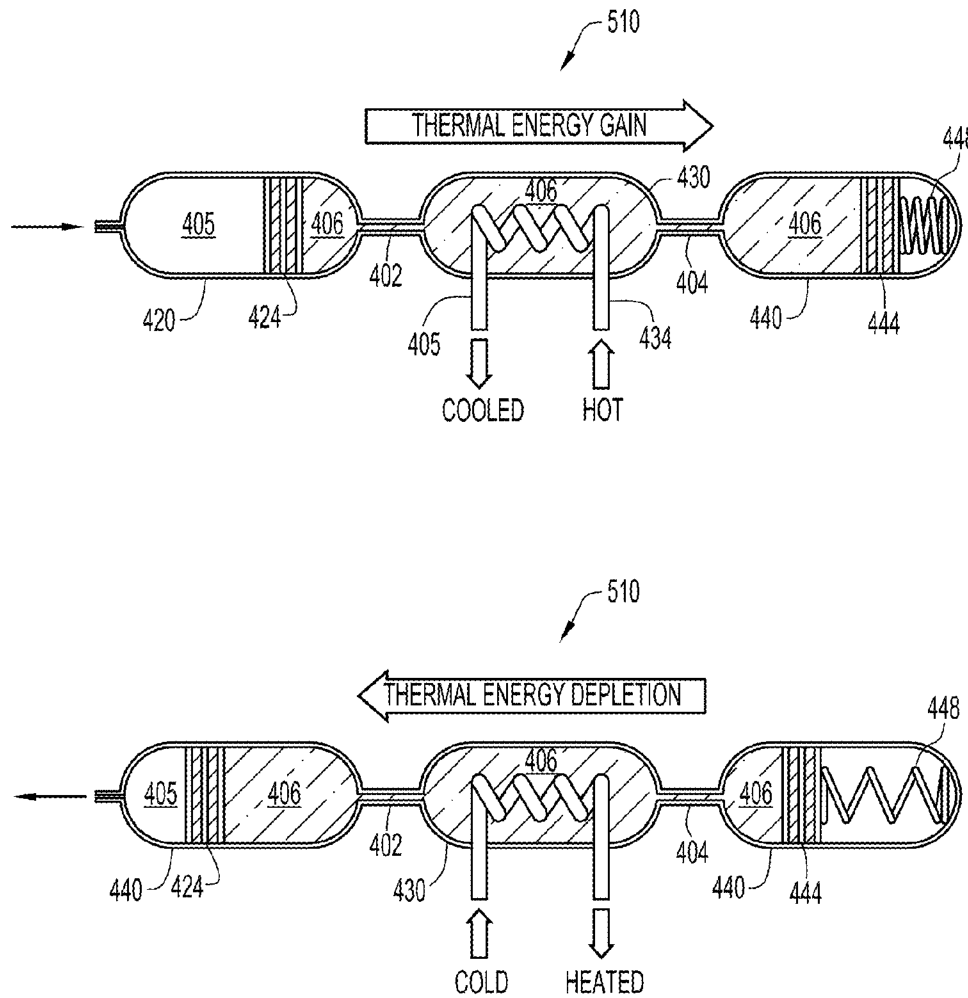

STORAGE EXPANSION VESSEL
446
448
440
444
406
442
404
430
AIR INLET / EXHAUST
TRANSFER / STORAGE VESSEL
434a
452
451
434b
AIR COMPRESSOR / MOTOR
432
450
402
ACCUMULATOR / RESERVOIR VESSEL
426
406
420
454
424
405
422
456
400
410
464
OTHER SENSORS
466
AIR PRESSURE SENSOR
468
BRAKING SENSOR
469
ACCELERATION SENSOR
470
474
SIGNAL CONDITIONERS
476
486
SYSTEM MONITOR
VEHICLE CONTROLLER
PROCESSOR
MEMORY
482
PNEUMATIC CONTROL
OTHER CONTROL
484
480
472a
DRIVER CIRCUITS
DRIVER CIRCUITS
472b
460
ECT
REGULATION AND CONTROL CIRCUITS
462
463

FIG.4



510
THERMAL ENERGY GAIN
448
406
430
405
406
406
402
404
420
424
405
434
440
444
COOLED
HOT
510
THERMAL ENERGY DEPLETION
448
406
405
406
406
402
404
440
424
430
440
444
COLD
HEATED

FIG.5

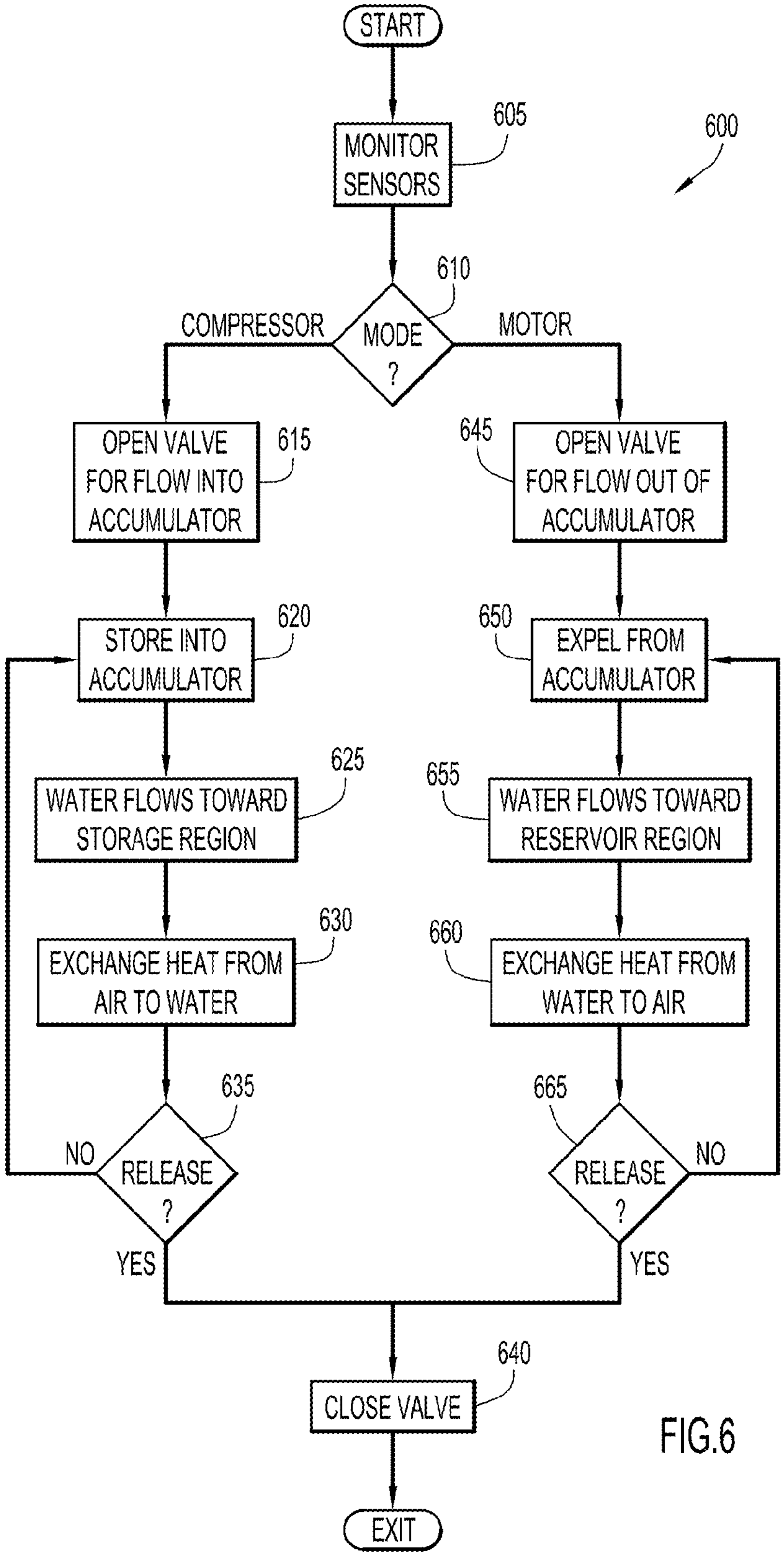

START
MONITOR SENSORS
605
600
610
COMPRESSOR
MODE ?
MOTOR
OPEN VALVE FOR FLOW INTO ACCUMULATOR
615
645
OPEN VALVE FOR FLOW OUT OF ACCUMULATOR
STORE INTO ACCUMULATOR
620
650
EXPEL FROM ACCUMULATOR
WATER FLOWS TOWARD STORAGE REGION
625
655
WATER FLOWS TOWARD RESERVOIR REGION
EXCHANGE HEAT FROM AIR TO WATER
630
660
EXCHANGE HEAT FROM WATER TO AIR
635
NO
RELEASE ?
YES
665
RELEASE ?
NO
YES
640
CLOSE VALVE
EXIT

FIG.6

THERMAL ENERGY RECOVERY

TECHNICAL FIELD

The present general inventive concept relates to thermal energy recovery.

BACKGROUND

Energy recovery, as used herein, encompasses a variety of techniques by which energy is transferred from one subsystem of a larger system to another in order to minimize the amount of energy that must be input to the system for it to perform its function. Energy recovery systems are being developed to counter increasing energy costs and to reduce pollutants and greenhouse gasses. Certain of these energy recovery techniques are referred to as "regenerative," meaning that energy is stored and then reapplied to do work. The most widespread example of this technology can be found in braking regeneration systems. These systems produce energy during braking in a way that can be readily stored, e.g., as electrical energy or hydraulic compression, as opposed to employing friction to brake, which generates heat that is usually just released into the brake's surroundings. The stored energy can be used to later supplement engine power, thereby effecting an improvement in overall fuel efficiency.

Recent advances in high pressure (6000-8000 psi), ruggedized, safe pneumatic components and subsystems have made pneumatic energy recovery a practical option, in many cases compressed air is used both as the energy storage medium and the working medium. Pneumatic energy recovery systems are generally smaller, lighter, and simpler than either of their electric or hydraulic counterparts.

A pneumatic energy recovery system, in its purest sense, has an optimized air compressor to store energy in the form of compressed air and a complementary air motor that operates on the expansion of air so as to utilize the stored energy in the compressed air to do work. The optimal configuration is a unified compressor and motor that can run in both directions, i.e., as a compressor and a motor, to implement thermodynamically reversible processes to the fullest extent practicable.

To ensure longevity, high performance and structural integrity of a combined compressor/motor, expanding and compressing gas must not exceed temperatures that cause component breakdown and the ability to shed heat is key to performance. While shedding heat in a compressor is one thing, increasing the temperature to expand air more efficiently in an air motor is typically overlooked, since such requires an additional energy source from which heat can be transferred. The development of thermal energy recovery techniques in a broader energy recovery context, such as in pneumatic regeneration systems must clearly be advanced.

SUMMARY

The present general inventive concept recovers thermal energy as part of a larger energy recovery scheme.

Certain aspects of the present general inventive concept implement thermal recovery through an accumulator that buffers a working fluid over an energy recovery cycle that includes a process in which working fluid is accumulated in the accumulator at increasing pressure. The energy recovery cycle includes another process that draws working fluid from the accumulator at decreasing pressure. A storage fluid conduit is in communication with the accumulator and stores an amount of a heat storage fluid. The heat storage fluid is displaced in the storage fluid conduit towards a heat storage region in response to increasing pressure of the working fluid in the accumulator. In response to decreasing pressure of the working fluid in the accumulator, the heat storage fluid is displaced within the storage conduit to a reservoir region. One or more heat exchange conduits traverse a boundary of the storage fluid conduit to come in thermal contact with the heat storage fluid. The heat exchange conduits convey the working fluid to transfer heat to the heat storage fluid during the process of the energy recovery cycle and to transfer heat from the heat storage fluid during the other process of the energy recovery cycle.

These and other objects, features and advantages of the present general inventive concept will be apparent from the following detailed description of illustrative embodiments thereof, which is to be read in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-1B are functional diagrams illustrating thermal energy recovery in a broader energy recovery context in embodiments of the present general inventive concept.

FIG. 2 is a diagram illustrating mechanisms by which heat exchange and heat storage may be implemented in embodiments of the present invention.

FIG. 3 is a diagram illustrating countercurrent flow heat exchange as implemented in embodiments of the present general inventive concept.

FIG. 4 is a schematic block diagram of a hybrid vehicle drive context in which the present general inventive concept can be embodied.

FIG. 5 is a diagram illustrating operation of a thermal energy recovery system in the hybrid vehicle drive of FIG. 4.

FIG. 6 is a flow diagram of thermal energy recovery process by which the present general inventive concept can be embodied.

DESCRIPTION OF EXAMPLE EMBODIMENTS

The present general inventive concept is best described through certain embodiments thereof, which are described in detail herein with reference to the accompanying drawings, wherein like reference numerals refer to like features throughout. It is to be understood that the term invention, when used herein, is intended to connote the inventive concept underlying the embodiments described below and not merely the embodiments themselves. It is to be understood further that the general inventive concept is not limited to the illustrative embodiments described below and the following descriptions should be read in such light.

Additionally, the word exemplary, when used herein, is intended to mean "serving as an example, instance or illustration." Any embodiment of construction, process, design, technique, etc., designated herein as exemplary is not necessarily to be construed as preferred or advantageous over other such embodiments. Particular quality or fitness of the examples indicated herein as exemplary is neither intended nor should be inferred.

Mathematical expressions are contained herein and those principles conveyed thereby are to be taken as being thoroughly described therewith. It is to be understood that where mathematics are used, such is for succinct description of the underlying principles being explained and, unless otherwise expressed, no other purpose is implied or should be inferred. It will be clear from this disclosure overall how the mathematics herein pertain to the present invention and, where embodiment of the principles underlying the mathematical expressions is intended, the ordinarily skilled artisan will recognize numerous techniques to carry out physical manifestations of the principles being mathematically expressed.

FIGS. **1**A-**1**B are illustrations of an energy recovery system **100** in which thermal energy recovery may be implemented by embodiments of the present invention. Broadly, energy recovery system **100** can be viewed as being carried out by a plurality of thermodynamic engines **110***a*-**110***e*, representatively referred to herein as thermodynamic engine(s) **110**, which, as used herein, is an abstraction to refer to any mechanism by which a change in a thermodynamic state, e.g., pressure, volume, temperature, etc., is effected through a transfer of energy, either as heat or by work. While thermodynamic engines **110** are illustrated to have similar appearance and are referenced in the illustration by common numeric indicators, thermodynamic engines may each operate under different process variables by entirely different mechanisms. The present invention is not limited to any particular physical manifestation of thermodynamic engines **110**; the skilled artisan will recognize numerous possible mechanisms that can be used to embody the present invention without departing from its intended spirit or scope. Indeed, it is to be understood that the use of the word "engine" is not strictly intended to mean "heat engine" in the traditional sense, although such an implementation of thermodynamic engines **110** is one possibility.

Thermodynamically, energy recovery system **100** is an open system where, in one process, i.e., that illustrated in FIG. **1**A, work is done on the system, such as by a shaft of compressor/motor **150** being externally driven, to compress a working fluid and to store the compressed fluid in a suitable working fluid storage facility **160**. In another process, i.e., the internal energy of the compressed working fluid stored in working fluid storage **160** is used by energy recovery system **100** to do work on its surroundings, such as to drive the shaft of compressor/motor **150**. Accordingly, the process illustrated in FIG. **1**A will be referred to as occurring while energy recovery system **100** is in compressor mode while the process illustrated in FIG. **1**B will be referred to as occurring while energy recovery system **100** is in motor mode. However, this nomenclature is not intended to restrict the present invention to a particular application.

As illustrated in FIGS. **1**A-**1**B, collectively referred to herein as FIG. **1** where no distinction is necessary, energy recovery system **100** is realized through a few basic components: compressor/motor **150**, heat exchanger **140**, heat storage facility **120** and working fluid storage facility **160**. Again, these components are abstractions that can be physically realized in a number of different ways, as the ordinarily skilled artisan will recognize and appreciate upon review of this disclosure. Compressor/motor **150** converts energy from mechanical work W to compress a working fluid from a low pressure P_L to a high pressure P_H, and to store the high pressure working fluid in working fluid storage **160**. This change in pressure carries with it a change in temperature from a low temperature T_L to a high temperature T_H. Heat exchanger **140** minimizes the difference between temperatures T_L and T_H by transferring heat to heat storage unit **140** to raise the temperature T_S of a heat storage medium. As will be discussed in detail below, minimizing the difference between temperatures T_L and T_H can improve the efficiency of compressor/motor **150**. In the reverse operation, the pressure of the working fluid stored in working fluid storage **160** is reduced from P_H to P_L in compressor/motor **150** to perform work W, which also causes a change in temperature from T_H to T_L. Heat exchanger **140**, to likewise improve efficiency, transfers heat to compressor/motor **150** to minimize the difference between temperature T_H and T_L. Of course, this description, as well as others herein, excludes consideration of system losses, but such losses are readily recognized by the skilled artisan and discussion of such is not necessary to practice the invention through its many possible embodiments. It is to be understood, however, that many modifications to embodiments described herein may be realized to minimize such system losses and other non-ideal behavior and the scope of the present invention is intended to encompass such variations.

Referring to FIG. **1**A, thermodynamic process **170** is described for compressor mode operation of energy recovery system **100**. Process **170** increases the pressure of the working fluid from P_L, indicated in the pressure-volume (PV) state diagram at **170***a*, to a pressure P_H indicated at **170***f*. In the illustrated embodiment, this change in pressure is achieved in stages, represented by thermodynamic engines **110***c*-**110***e* by mechanical work W. It is to be understood that while only three stages are illustrated, the present invention is not so limited. Additionally, while is it illustrated that work W is done on each stage **110***c*-**110***e*, such work may be derived from a common mechanism.

In stage **110***c*, work is done on the working fluid to increase the pressure by an increment $\Delta P_c=P_1-P_L$, corresponding to path **170***a*' to **170***b* in process **170**, where the subscript on the increment notation refers to the thermodynamic engine **110** by which the increment is achieved. The increase in pressure causes an incremental increase in temperature $\Delta T_c=T_2-T_L$. Thermodynamic engine **110***a* in heat exchanger **140** transfers heat from the working fluid to the heat storage medium in heat storage **120** to reduce the temperature by an increment $\Delta T_a=T_1-T_2$, which, to be noted, is a negative value. If held at constant pressure, this change in temperature ΔT_c compels a change in volume of the working fluid, by which less effort is required to transfer the working fluid into a smaller working volume of subsequent compressor stage **110***d*. The skilled artisan will recognize this process as similar to "intercooling" in a multistage compressor. The change in temperature and corresponding change in volume occur nearly isobarically, as illustrated at process path **170***b*-**170***c*. Compression/heat exchange processes similar to that just described are performed in process **170** to obtain a final working fluid pressure. That is, a change of pressure $\Delta P_d=P_2-P_1$ and temperature $\Delta T_d=T_3-T_1$ may be brought about at stage **110***d*, as indicated at process path **170***c*-**170***d*. Subsequently, a change in temperature $\Delta T_b=T_2-T_3$ is achieved by heat transfer in thermodynamic engine **110***b*, which causes a decrease in volume of the working fluid. This concurrent change of thermodynamic state is indicated at process path **170***d*-**170***e*. The working fluid is compressed to its final pressure P_H by a incremental increase $\Delta P_e=P_H-P_2$ and increase in temperature $\Delta T_e=T_H-T_2$, as indicated at process path **170***e*-**170***f*. The working fluid may then be transferred at this pressure P_H and temperature T_H to working fluid storage **160**.

As stated above, minimizing the difference between temperatures TH and TL may improve the efficiency of energy recovery system **100**. In the PV diagram of FIG. **1**A, curve **172** indicates an adiabatic path that might be traversed without the multistage compression/intercooling operation described above and curve **174** indicates a isothermal path that might be traversed in an ideal case. The difference between these two paths represents the difference between the amount of work that be done to achieve the same final pressure. Thus, the shaded area **179** corresponds to an amount of work that need not be done on energy recovery system **100** as compared to a system in which a single stage compressor might be employed. More significantly, however, is that in accordance with the present invention, stored heat can be provided to the working fluid to achieve similar energy savings when energy recovery system **100** is in the motor mode of operation, as described with reference to FIG. **1**B.

Motor mode process **180** of energy recovery system **100** is essentially the reverse of process **170** and, ideally if such were possible, would be exactly the reverse process. In the exactly reverse process, energy system **100** would be capable doing the same work for a given amount of pressurized working fluid that was done on the system to store that amount of working fluid. For purposes of understanding the basic principles of the processes of the energy recovery cycle, which consists of process **170** and complementary process **180**, embodiments of the present invention seek to implement motor mode process **180** as the reverse of compression mode process **170** to the extent possible and, as such, the explanation of motor mode process will be abbreviated. The ordinarily skilled artisan will recognize and appreciate the impediments to achieving the perfectly reverse thermodynamic path without an accounting thereof in the present explanation.

Motor mode process **180** converts the energy stored as pressure of the working fluid stored in working fluid storage **160** to kinetic energy of work W. Thus, at the completion of the process, the pressure of the working fluid drops from pressure PH, indicated at state **180***f* in the PV diagram, to a pressure PL indicated at state **180***a*. The work is done over stages by thermodynamic engines **110***c*-**110***e*, such as by incrementally rotating a shaft by means of a crankshaft, although the present invention is not so limited. In complementary fashion to the volumetric compression by heat transfer between each stage **110***c*-**110***e*, a volumetric expansion occurs in motor mode process **180** by transferring heat from heat storage **120** to the working fluid through thermodynamic engines **110***a*-**110***b* as the working fluid proceeds through stages **110***c*-**110***e*. Thus, in a reverse manner to that explained above, stages **110***e*-**110***c* do work through volumetric expansion with a corresponding drop in pressure and temperature as indicated at paths **180***f*'-**180***e*, **180***d*-**180***c* and **180***b*-**180***a*', respectively. In concert with the transfer of the working fluid through stages **110***e*-**110***c*, thermodynamic engines **110***b*-**110***a* add heat to the working fluid to cause isobaric expansion of the working fluid as indicated at paths **180***e*-**180***d* and **180***c*-**180***b*.

The physical manifestation of thermodynamic engines **110***a* and **110***b* dictate to a great extent the efficiency of energy recovery system **100**. Any implementation must be adapted to the heat storage medium used in heat storage **120** and to transfer heat in an efficient manner. Additionally, thermodynamic engines **110***a* and **110***b* are to transfer heat in both directions across the working fluid/heat storage medium boundary, which requires that the heat storage medium must be colder than the temperature of the working fluid at respective thermodynamic engines **110***a* and **110***b* during compression mode process **170** and hotter than the working fluid at respective thermodynamic engines **110***a* and **110***b* during motor mode process **180**. While there are many ways to achieve these conditions, not all solutions are suitable for energy recovery. That is, energy that is consumed to compel a particular process to occur cannot be stored as recovered energy.

FIG. **2** is a diagram illustrating mechanisms by which heat exchange and heat storage may be implemented in embodiments of the present invention. As used herein, these mechanisms together form a thermal energy recovery system **200** and perform a thermal recovery process. It is to be understood that the illustration of FIG. **2** is composed for purposes of explaining the invention in an implementation-neutral context and, as such, various mechanisms to enhance the thermal recovery process, such as fins, etc., are not illustrated in the figure. The skilled artisan will recognize numerous techniques and physical structures by which the system illustrated in FIG. **2** can be made more efficient, some of which are described below. The scope of applicability of the present invention is intended encompass all such implementation details.

In the thermal energy recovery system **200** of FIG. **2**, a thermal energy storage fluid **215** is chosen to have properties to meet the application in which the present invention is embodied. To meet the bi-directional flow of heat described above, the material chosen for storage fluid **215** should be suitable for service as both a heat exchange medium and a heat storage medium. Both of these conditions can be met with a material that has a high specific heat capacity. Water has a particularly high specific heat density, but has a narrow operating range, i.e., water has phase transition boundaries at 0° C. and 100° C. While the present invention is not limited to a particular storage fluid **215**, water will be assumed in the embodiments described below and techniques that ameliorate the narrow operating range of water as storage fluid **215** are described below as well.

As illustrated in FIG. **2**, an amount of storage fluid **215** is contained in a conduit **210**. In certain embodiments, the amount of storage fluid is fixed in that it does not change over time. In the illustrated example, the amount of storage fluid **215** in conduit **210** is $\rho_S V_S$ where ρ_S is the density of storage fluid **215** and V_S is the volume of the fluid. Diagrammatically, the amount of storage fluid **215** in conduit **210** is represented by the fluid column having diameter D**1** and length L_S. The amount of storage fluid **215** should be carefully considered in view not only of the number of different roles it must fulfill thermodynamically, but also in view of the mechanics of thermal recovery system **200**, as will be discussed further below and the constraints on the platform in which thermal recovery system **200** is implemented.

Conduit **210** may have a length L_C that is greater than the length L_S of the column of storage fluid **215** so that storage fluid **215** can be displaced therein. Conduit **210** may be delineated into three regions: a reservoir region **232**, a transfer region **234** and a storage region **236**. This delineation should not be construed as defining specific boundaries; the extent of these regions extends to the limits of the effects of the processes occurring in and around these regions. However, certain embodiments of the invention impose physical boundaries to enforce a separation of storage fluid **215** by various thermodynamic states, such as temperature. Generally, storage fluid **215** in reservoir region **232** is colder than that in storage region **236** and desirably, storage fluid **215** in reservoir region **232** will be at the lowest temperature available for the given system, such as the platform ambient temperature, and storage fluid **215** in storage region **236** will be the maximum temperature achievable through heat transfer from working fluid. The relative lengths L_C and L_S may be such that, at any moment in time, either of reservoir region **232** or storage region **236** may be empty, in which case the other of storage region **236** or reservoir region **232** is not empty. Transfer region **234** may always be occupied by storage fluid **215** and, as such, storage fluid **215** in transfer region **234** may form a part of the heat storage mass, as will be clear from discussions below.

A conduit **220** of diameter $D_2<D_1$ may traverse the boundary of conduit **210** so as to be in thermal contact with storage fluid **215**. A working fluid **225** may flow through conduit **220** under the influence of a motivating force $\vec{F}_3$. Heat flows across the boundary of conduit **220** either to storage fluid **215** or to working fluid **225** depending on the process of the energy recovery cycle that is active.

As illustrated in FIG. **2**, opposing forces $\vec{F}_1$ and $\vec{F}_2$ may be applied to establish a net force $\vec{F}_S=\vec{F}_1-\vec{F}_2$ on storage fluid **215**. Forces $\vec{F}_1$ and $\vec{F}_2$ can be dynamically controlled so that the net force $\vec{F}_S$ applies a specific level of pressure on storage fluid **215** and at the same time motivates storage fluid **215** through conduit **210** in a specific direction. For example, in the configuration illustrated in FIG. **2**, net force $\vec{F}_S$ compels storage fluid to flow towards storage region **236** and heat is transferred from working fluid **225** to storage fluid **215**. This transfer corresponds to the compression mode process of the energy recovery cycle described with reference to FIG. **1** and results in an energy gain, i.e., a net increase of thermal energy in storage fluid **215**. In the motor mode of the energy recovery cycle, heat is transferred from storage fluid **215** to working fluid **225**, which results in energy depletion, i.e., a net decrease of thermal energy in storage fluid **215** has occurred.

For purpose of describing thermal energy recovery system **200**, an arbitrary initial state is assumed, i.e., that at an initial time t_0^-, reservoir region **232** is substantially occupied by storage fluid **215** and that the temperature of storage fluid **215** in reservoir region **232** is T_A. Additionally, it is to be assumed that transfer region **234** is also occupied by storage fluid **215**, also at temperature T_A, and that storage region **236** is substantially empty. At time t_0, a compression mode process begins and, accordingly, working fluid **225** begins to flow in conduit **220** in a direction indicated by the working fluid flow direction arrow at a velocity $\vec{v}_W$ owing to the influence of $\vec{F}_3$. It is to be assumed that working fluid **225** is at a temperature $T_C>T_A$ when it traverses the boundary of conduit **210**. Accordingly, heat is transferred by conduction across the boundary of conduit **220** from working fluid **225** to storage fluid **215** and the temperature of storage fluid **215** in transfer region **234** begins to rise. At time $t_1 \geq t_0$, forces $\vec{F}_1$ and $\vec{F}_2$ are applied at relative magnitudes so that storage fluid **215** is compelled to move through conduit **210** at a velocity $\vec{v}_S$ in the flow direction indicated by the storage fluid flow direction arrow illustrated in FIG. **2**. Such flow establishes forced convection, for purposes of transferring heat more efficiently, while also moving the heated storage fluid **215** into storage region **236**. In certain embodiments, forces $\vec{F}_1$, $\vec{F}_2$ and $\vec{F}_3$ are controlled to establish a mass flow rate in each of working fluid **225** and storage fluid **225** by which maximum heat transfer can be achieved for the specific heat capacities of each fluid. Additionally, pressure applied by forces $\vec{F}_1$ and $\vec{F}_2$ may be made sufficient to prevent a phase change in storage fluid **215**, thereby extending its operating range as a heat exchange/heat storage medium. That is, as the temperature increases in storage fluid **215**, so too does the pressure if the volume is kept constant by forces $\vec{F}_1$ and $\vec{F}_2$ and, of course, the containing walls of conduit **210**. If sufficient pressure builds in water, for example, it can become superheated rather than undergoing a phase change to vapor. As such, added heat will continue to increase its temperature, at least up to the point where the fluid becomes critical.

At time $t_2>t_1$, the compressor mode process terminates at which time $\vec{F}_3$ becomes zero and the flow of working fluid **225** ceases. At time $t_3 \geq t_2$, flow of storage fluid **215** is terminated by asserting $\vec{F}_1=\vec{F}_2$. In this condition, heated storage fluid **215** is held in storage region **236** and heat transfer will continue in transfer region **234** until thermal equilibrium is reached between the walls of conduit **220** and storage fluid **215**. Thermal energy recovery system **200** remains in this condition until, at time $t_4>t_3$, the energy recovery cycle enters its motor mode process, and the operation of thermal recovery system **200** is reversed.

In certain embodiments of the present invention, the flow directions of working fluid **225** and storage fluid **215** are in continual opposition, i.e., the flows are in opposite directions in both compressor and motor mode processes. This countercurrent exchange achieves greater heat transfer than can be obtained through concurrent flow heat exchange, i.e., where the fluids flow in the same direction. This is explained with reference to FIG. **3**, where both concurrent and countercurrent heat exchange configurations are illustrated. In both the concurrent exchange case **310** and the countercurrent exchange case **340**, flows are to be considered as being in thermal contact, despite being illustrated as being separated. It is to be assumed for purposes of the following discussion that both systems **310** and **340** are equivalent except for the flow direction and fluid entry points. It is to be assumed as well that a hot fluid and a cold fluid enter their respective conduits at a constant temperature, i.e., heat is not transferred to the respective fluid sources. Additionally, once the fluids exit their respective conduits, no further heat exchange occurs between the fluids. These assumptions and constraints are only imposed for purposes of analysis so that the differences between the two configurations are readily identified and understood.

In concurrent exchange configuration **310**, the hot and cold fluids **325** and **335**, respectively, enter at the same ends **322** and **332** of respective conduits **320** and **330** and flow in the same direction. Given the constraints above, the temperature gradient at the input ends **322** and **332** is constant and fixed by the entry temperatures of hot and cold fluids **325** and **335**. Thus, at entry end **322** and **332**, there is a substantial temperature gradient, as indicated by the parallel lines between conduits **320** and **330** (and conduits **350** and **360** in the countercurrent exchange case **340**), where more closely spaced lines indicate a higher temperature gradient than lines that are separated further apart. During transport, heat is transferred from hot fluid **325** to cold fluid **335** along the lengths of conduits **320** and **330**, thus causing an incremental temperature increase in cold fluid **335** and an incremental temperature decrease in hot fluid **325**, which diminishes the temperature gradient between the two fluids along the lengths of conduits **320** and **330**. This heat exchange continues as fluids **325** and **335** flow towards the exit ends of conduits **320** and **330**, respectively, until at the exit end (assuming adequate lengths of the conduits), fluids **325** and **335** exit in thermal equilibrium at a temperature that is almost exactly midway between the original temperatures of hot fluid **325** and cold fluid **335** at entry ends **322** and **332**. If thermal equilibrium is reached at a point along conduits **320** and **330** prior to fluids **325** and **335** reaching exit ends **324** and **334**, no further heat transfer occurs from that point onward along the remaining length of conduits **320** and **330**.

In the countercurrent exchange configuration **340**, hot fluid **355** enters conduit **350** at an end **352** opposite end **362** at which cold fluid **365** enters conduit **360**. Conduit **360** is thus always cold at its entry end **362** and conduit **350** is always hot at its entry end **352**. During transport, heat is transferred from hot fluid **355** to cold fluid **365** thus causing an incremental increase in the temperature of cold fluid **365** along conduit **360** and a corresponding incremental decrease in the temperature of hot fluid **355** along conduit **350**. However, in contradistinction to the concurrent exchange configuration **310**, hot fluid **355** flows in the direction of the coldest point of conduit **360** and cold fluid **365** flows in the direction of the hottest point of conduit **350**. Thus, the energy transferred across conduits at any point along conduits **350** and **360** is offset by material transport in both conduits **350** and **360** towards a lower and higher temperature, respectively, fixed by the entry temperatures of the two fluids. This results in a near constant temperature gradient along the entire lengths of conduits **350** and **360** and a corresponding constant transfer of heat along that entire length. Given sufficiently long conduit lengths, the exit temperature of fluid **355** is very near the entry temperature of cold fluid **365** and the exit temperature of fluid **365** is very near the entry temperature of hot fluid **355**. From this first order analysis, it will be readily appreciated by the skilled artisan that the countercurrent exchange configuration **310** achieves greater heat transfer than the concurrent configuration **340**.

Returning to FIG. **2**, compelling storage fluid **215** and working fluid **225** into respective flows requires that work be done on these fluids. While the force $\vec{F}_3$ moving working fluid **225** is provided by compressor/motor **150**, for example, the energy to impart forces $\vec{F}_1$ and $\vec{F}_2$ must be must somehow be provided. As indicated above, any energy consumed to do the work of these forces must be deducted from the energy recovered by energy recovery system **100**. Thus, employing a pump or similar mechanism would be poor candidates for an efficient energy recovery implementation. Instead, certain embodiments of the present invention utilize the pressure of the working fluid **225** to displace storage fluid **215**. A working fluid buffer **250** may contain an amount of pressurized working fluid to apply, for example, $\vec{F}_1$. Thus, as pressurized working fluid **225** is stored as part of the energy recovery process, a portion of that working fluid can be buffered to compel storage fluid **215** towards storage region **236**. $\vec{F}_2$ may be implemented by a suitable mechanical energy storage device that opposes the $\vec{F}_1$. As pressure is drawn off in motor mode process **180**, $\vec{F}_1$ may diminish or terminate. In either case, potential energy at the opposing end of the storage fluid column, when properly realized, can provide the energy for $\vec{F}_2$ to drive storage fluid back towards reservoir region **232**. Thus, $\vec{F}_2$ may be realized by any suitable mechanism that implements an elastic bias, such as a spring or a suitable gas. The present invention is not limited to this configuration; other techniques may be used with the present invention to bring about the storage fluid flow without departing from the spirit and intended scope of the present invention.

FIG. **4** is a schematic block diagram of an embodiment of a thermal energy recovery system **410** of the present invention incorporated into a pneumatic drive system **400** of a hybrid vehicle (not illustrated). In the exemplary pneumatic drive system **400**, the working fluid is air **405** and the heat storage fluid is water **406**, although the present invention is not restricted to these fluids. Thermal energy recovery system **410** includes an accumulator/reservoir vessel **420**, heat transfer/storage vessel **430** and storage expansion vessel **440** that are interconnected by suitable piping **402** and **404**. Together these components form the storage fluid conduit previously described; water **406** is displaced across the vessels **410**, **430** and **440** between reservoir region **426**, transfer region **432** and storage region **442** in the same manner as that generally described with reference to FIG. **2**. In system **410**, however, physical boundaries are imposed between the regions **426**, **432** and **442**, i.e., by the walls of vessels **420**, **430** and **440**. This division can beneficially isolate portions of water **406** thermodynamically, while piping **402**, **404** provides the ability to move the water between vessels by forces applied at the ends of the water column, i.e., at interfaces **424** and **444**, to compel a flow.

In thermal recovery system **410**, the working fluid storage facility described as working fluid storage **160** in FIG. **1** is implemented in a common vessel, i.e., accumulator/reservoir vessel **420**, with reservoir region **426**. Accordingly, the accumulated volume of pressurized air applies the storage fluid motivating force, described as force $\vec{F}_1$ in FIG. **2**. Thus, the functionality of the working fluid buffer **250** described in FIG. **2** is also implemented by accumulator/reservoir vessel **420**. Pressure is applied to the air/water interface **424** and a volume of water **406** is displaced by a corresponding volume of air **405**. Interface **424** may be a piston, bladder or other mechanism that moves under sufficient pressure. In certain embodiments, the air pressure in accumulator **405** can range from about 500 psig (about 3.447 MPa) to about 6,000 psig (about 41.37 MPa) or 8,000 psig (about 55.16 MPa), but the present invention is not limited to these ranges. At the other end of the water column, a spring **448** or other biasing mechanism is situated in space **446** of storage expansion vessel **440** and applies the force described in FIG. **2** as force $\vec{F}_2$ and interface **444** may be implemented by, for example, a piston. The spring coefficient of spring **448** should be chosen in accordance with the expected storage pressure in accumulator **422** to ensure proper flow and proper pressure on the water column to prevent a vapor phase transition within the temperature range of interest, i.e., the expected maximum temperature of the water.

Transfer/storage vessel **430** isolates the heat transfer region **432** from the reservoir region **426** and the storage region **442**. A plurality of intercooler heat exchange tubes **434***a* and **434***b*, representatively referred to herein as heat exchange tube(s) **434**, traverse the wall of transfer/storage vessel **430** to be placed in thermal contact with water **406** in heat transfer region **432**. Heat exchange tubes **434** may be suitably constructed for efficient heat exchange, such as by implementing fins, coils, meanderings, or other structures that increase the surface area over which heat is exchanged by conduction between air **405** in heat exchange tubes **434** and water **406** within transfer/storage vessel **430**.

As previously stated, in the example application illustrated in FIG. **4**, pneumatic drive system **400** is incorporated into a hybrid vehicle. It is to be understood that the operational details of the vehicle in which pneumatic drive system **400** is incorporated is not essential to understanding the role of thermal recovery system **410** in that vehicle. However, description of certain functions of the vehicle are believed useful, particularly since the operation of thermal recovery system **400** is dependent on the process of the energy recovery cycle that pneumatic drive system **400** implements, i.e., regenerative braking, which, in turn, relates to operations of the vehicle that initiate those processes. Briefly, shaft **451** of compressor/motor **450** may be coupled to the main drive shaft (not illustrated) by means of an electrically-controlled clutch/transfer drive (ECT) **462** that is controlled by vehicle controller **470** in the vehicle's electrical system **460**. ECT **462** is an abstraction of several devices that may be used to mechanically couple compressor/motor **450** with the drive shaft of the vehicle on demand and to make any speed or torque conversions between shaft **451** and the vehicle drive shaft. Again, the implementation details of the coupling of compressor/motor **450** with the vehicle drive train are not essential to practice the present invention. ECT **462** is engaged for the compressor mode during braking and for the motor mode for acceleration, subject to certain conditions, such as the availability of a sufficient amount of compressed air.

Vehicle electrical system **460** includes a number of sensors, a number of regulation and control circuits and a vehicle controller **470**. The sensors may include an air pressure sensor **466** that monitors the air pressure in accumulator **422**, a braking sensor that generates a signal when the vehicle's brake pedal is depressed to a certain level, an acceleration sensor **469** that generates a signal when the vehicle's accelerator pedal is depressed to a certain level, and other sensors **464** that monitor other vehicle functions. Control mechanisms may include an electrically operated air valve **456**, ECT **462** and other regulation and control circuits **463** that operate various system components by way of control signals generated by vehicle controller **470**. Vehicle controller **470** may include signal conditioning circuits **474** that, among other things, filter incoming signals and convert analog signals to digital data signals, and various drive circuits that, among other things, convert where necessary digital data signals to analog signals and amplify and buffer the electrical signals provided to the various regulation and control circuits. Vehicle controller **470** may also include a processor **480**, which may be implemented in fixed or programmable logic including, but not limited to, application specific circuits, programmable logic arrays, microprocessors and microcontrollers. Memory **476** may provide storage for process data and, when processor **480** is a programmable microprocessor, processor instructions that when executed, perform various monitoring and control functions. Processor **480** may execute, either by fixed circuitry or by executing program code, system monitoring process **486** that continuously monitors available sensors for various conditions, pneumatic control process **482** that operates pneumatic drive system **400** and other control functions **484** to operate other various vehicle subsystems.

In operation, the hybrid vehicle may be operated as would any vehicle be operated. Inevitably, the vehicle operator will have to brake and, if the pressure on the brake pedal is above a certain threshold, as determined from braking sensor **468** and system monitor **486**, then pneumatic drive system **400** is operated into the compressor mode and compressor mode process **170** may be initiated. Pneumatic control process **482** may generate a signal that operates ECT **462** to mechanically couple shaft **451** of compressor/motor **450** to the vehicle drift shaft. In response, ambient air is drawn into compressor/motor **450** through inlet **452** and compressed in stages as described with reference to FIG. **1**. Pneumatic control process **482** may generate an additional signal that operates valve **456** into a state that allows air flow into accumulator **422** but not in the opposite direction. As air **405** is compressed, it passes through intercooler heat exchange tubes **430***a* and **430***b*, and heat is transferred to water **406** in transfer/storage vessel **430**. The fully compressed air exits compressor/motor **450** through pressurized air line **454**, through valve **456** and into accumulator **405**. When sufficient air pressure is built, the air in accumulator **422** exerts sufficient for to displace interface **424** and with it, as illustrated more clearly by configuration **510** in FIG. **5**, water **406** through piping **402** across heat exchange tube **434** in transfer/storage vessel **430** and into storage expansion vessel **440**. The displacement of water **406** in storage expansion vessel **440** displaces interface **444** to compress spring **448**. It is to be noted that countercurrent heat exchange, as described in FIG. **3**, occurs in transfer/storage vessel **430**.

In keeping with regenerative braking principles, the braking of the vehicle is achieved by transferring energy from the vehicle's drive train to do work on compressor/motor **450** by way of shaft **451**. Accordingly, certain embodiments of the invention may determine, such as from the pressure on and duration over which the brake pedal is depressed, whether to engage, either partially, fully or not at all, the friction brakes of the vehicle.

At some point, vehicle controller **470** will terminate the regenerative braking and with it compressor mode process **180**. This may occur when the brake pedal is released, when maximum air storage capacity is reached, or other conditions per the vehicle's design. Accordingly, pneumatic control process **482** may generate a signal to close valve **456** so that air can neither enter nor exit accumulator **422**. Additionally, pneumatic control process **482** may generate another signal to disengage the vehicle drive from compressor/motor shaft **451** by way of deactivating ECT **462**. Pneumatic drive system **400** will remain in this standby state until another braking event or until an acceleration event initiates a motor mode process **180**.

At some point during vehicle operation, added power may be desired, such as when greater acceleration is called for. Accordingly, the vehicle operator may depress the accelerator pedal and a signal indicative of such will be generated by acceleration sensor **469**. System monitor may determine if certain conditions are met prior to initiating motor mode process **180**, such as to the manner in which the accelerator pedal was depressed, e.g., how rapidly and how far the pedal is depressed, and whether sufficient air is stored to meet the acceleration demand. The amount of pressurized air in accumulator **422** may be monitored by air pressure sensor **466**. If all of the necessary conditions are met, processor **480** may initiate motor mode process **180**. Pneumatic control process **482** may generate a signal to couple the vehicle's drive train to compressor/motor shaft **451** by engaging ECT **462**. Pneumatic control process **482** may generate another signal to operate valve **456** into an open position that allows air **405** to flow out of accumulator **422**, but not into accumulator **422**. In response, air **405** flows out of accumulator **422**, through valve **456** and air line **454**, and into compressor/motor **450**. Air **405** in compressor/motor **450** expands across the different stages, as described with reference to FIG. 1B, to rotate shaft **451**. Air **405** traverses the stages through heat exchange tubes **434**, where heat is transferred from heated water **406** in transfer/storage vessel **430** to air **405** in heat exchange tubes **434**. The decompressed air exits compressor/motor **450** at exhaust port **452**. Meanwhile, as air **405** exits accumulator **422**, the lost volume allows spring **448** to expand to thereby displace interface **444**. As illustrated in configuration **520** in FIG. **5**, as interface **444** is moved, so too is water **406** in storage expansion vessel **440**, in piping **404**, in transfer/storage vessel **430**, in piping **402** and in accumulator/reservoir vessel **420**. The force of spring **448** is ultimately felt by interface **424** which is moved to displace the evacuated air. Upon termination of the acceleration event, either by, for example, removing pressure from the accelerator pedal or by virtue of insufficient air pressure to continue, motor mode process **180** is terminated by closing valve **456** and disengaging compressor/motor shaft **451** from the vehicle's drive train, such as by deactivating ECT **462**.

FIG. **6** is a flow diagram of thermal energy recovery process **600** by which the present invention can be embodied, which again assumes air as the working fluid and water as the heat storage fluid. In operation **605**, sensors are monitored various system conditions and/or events. In operation **610**, it is determined whether criteria are met for either compressor mode process **170** or motor mode process **180**. In the case of compressor mode, thermal energy process **600** transitions to operation **615**, where a valve governing the flow into and out of an air storage accumulator is opened to allow air to flow into the accumulator, which occurs by operation **620**. In operation **625**, by the action of air entering the accumulator, water flows towards a heated water storage region and by the action of water flowing toward the storage region, heat is transferred in a transfer region from the air to the water. In operation, **635**, it is determined whether the compressor mode process is released, i.e., has completed to the extent required by system conditions, and, if not, air continues to be stored at operation **620**. If on the other hand the compressor mode process has been released, the air valve to the accumulator is closed.

If, in operation **610**, it is determined that system conditions meet criteria for motor mode operation, the accumulator valve is opened in operation **645** to allow air flow out of the accumulator, which occurs in operation **650**. By the action of air exiting the accumulator, water flows toward the reservoir region in operation **655** and by this action, heat is exchanged in the transfer region from the water to the air. In operation **665**, it is determined whether the motor mode process is released and, if so, the accumulator valve is closed. If the motor mode process is not released, air continues to exit the accumulator at operation **650**.

The descriptions above are intended to illustrate possible implementations of the present inventive concept and are not restrictive. Many variations, modifications and alternatives will become apparent to the skilled artisan upon review of this disclosure. For example, components equivalent to those shown and described may be substituted therefore, elements and methods individually described may be combined, and elements described as discrete may be distributed across many components. The scope of the invention should therefore be determined not with reference to the description above, but with reference to the appended claims, along with their full range of equivalents.

What is claimed is:

1. An apparatus comprising:

an accumulator to buffer a working fluid over an energy recovery cycle that, by one process thereof, accumulates working fluid in the accumulator at increasing pressure and, by another process thereof, draws from the working fluid from the accumulator at decreasing pressure;

a storage fluid conduit in communication with the accumulator and storing an amount of a heat storage fluid therein such that, in response to increasing pressure of the working fluid in the accumulator, the heat storage fluid is displaced within the storage fluid conduit to a heat storage region and, in response to decreasing pressure of the working fluid in the accumulator, the heat storage fluid is displaced within the storage conduit to a reservoir region; and

at least one heat exchange conduit traversing a boundary of the storage fluid conduit to be in thermal contact with the heat storage fluid therein, the heat exchange conduit conveying the working fluid to transfer heat to the heat storage fluid during the process of the energy recovery cycle and to transfer heat from the heat storage fluid during the other process of the energy recovery cycle.

2. The apparatus of claim **1** further comprising:

an accumulator/reservoir vessel to enclose the accumulator and reservoir region in common containment;

an interface displaceable within the accumulator/reservoir vessel and mechanically separating the buffered working fluid and the heat storage fluid therein; and

an expansion vessel applying mechanical force to the heat storage fluid in the heat storage region so that, in response to the decreasing pressure of the buffered working fluid in the accumulator/reservoir vessel, the heat storage fluid is motivated to the reservoir region by the applied mechanical force.

3. The apparatus of claim **2**, wherein the expansion vessel includes an elastic biasing device that opposes motion of the heat storage fluid therein to apply the mechanical force.

4. The apparatus of claim **3**, wherein the biasing device is a spring.

5. The apparatus of claim **3**, wherein the biasing device is a quantity of compressible gas.

6. The apparatus of claim **2** further comprising:

a valve at a working fluid entry port of the accumulator/reservoir vessel that prohibits flow of the working fluid in a closed position thereof, allows unidirectional flow of the working fluid into the accumulator/reservoir vessel in an open position and allows unidirectional flow of the working fluid out of the accumulator/reservoir in another open position.

7. The apparatus of claim **6** further comprising:

a processor configured to:

determine whether the process or the other process of the energy recovery cycle is initiated;

generate a valve control signal to:

compel the valve into the open position responsive to the determination that the process of the energy recovery cycle is initiated;

compel the valve into the other open position responsive to the determination that the other process of the energy recovery cycle is initiated; and

compel the valve into the closed position otherwise.

8. The apparatus of claim **1**, wherein the working fluid is compelled to flow in the heat exchange conduit in a direction opposite to the flow of the heat storage fluid in both the process of the energy recovery cycle and the other process of the energy recovery cycle.

9. The apparatus of claim **1**, wherein the at least one heat exchange conduit includes a plurality of heat exchange conduits traversing the boundary of the storage fluid conduit, where the working fluid in each of the heat exchange conduits are in a thermodynamic state distinct from the working fluid in the others of the heat exchange conduits.

10. An apparatus comprising:

an accumulator/reservoir vessel to store a working fluid over an energy recovery cycle that, by one process thereof, accumulates the working fluid in an accumulator region of the accumulator/reservoir vessel at increasing pressure and, by another process thereof, draws from the working fluid from the accumulator region at decreasing pressure, the accumulator/reservoir vessel including a reservoir region to store a heat storage fluid therein, the reservoir region having an elastic boundary that remains in contact with both the working fluid in the accumulator region and the heat storage fluid as the pressure of the working fluid in the accumulator region increases and decreases;

a storage expansion vessel storing the heat storage fluid in a heat storage region thereof, the heat storage region having an elastic boundary that remains in contact with the heat storage fluid as the heat storage fluid is displaced to occupy the reservoir region;

a transfer/storage vessel in fluid communication with the reservoir region of the accumulator/reservoir vessel and with the heat storage region of the storage expansion vessel, the transfer/storage vessel being in constant occupancy by the heat storage fluid as the heat storage fluid is displaced to occupy the reservoir region; and

at least one heat exchange conduit traversing a boundary of the transfer/storage vessel to be in thermal contact with the heat storage fluid therein, the heat exchange conduit conveying the working fluid to transfer heat to the heat storage fluid during the process of the energy recovery cycle and to transfer heat from the heat storage fluid during the other process of the energy recovery cycle.

11. The apparatus of claim **10**, wherein the elastic boundary of the storage expansion vessel is elastically biased in opposition to the displacement of the heat storage fluid into heat storage region to apply a force to the heat storage fluid towards the reservoir region of the accumulator/reservoir vessel.

12. The apparatus of claim **11**, wherein a force on the heat storage fluid by the pressure of the working fluid in the accumulator region and the force on the heat storage fluid by the elastically biased boundary of the heat storage region combine to apply pressure to the heat storage fluid that is sufficient to raise a phase transition temperature of the heat storage fluid.

13. The apparatus of claim **10**, wherein the at least one heat exchange conduit includes a plurality of heat exchange conduits traversing the boundary of the transfer/storage vessel, where the working fluid in each of the heat exchange conduits are in a thermodynamic state distinct from the working fluid in the others of the heat exchange conduits.

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